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Multiple-perspective Reorganisation of the Dairy sector: Mathematical Programming Approach

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Abstract

Background: Agriculture is a production system in which the economic principles of organisation act in mutual dependence with its ecological boundaries. **Objectives:** Building on this premise, the paper evaluates performance of a chosen agricultural production system (dairy production in Slovenia) from two complementary perspectives, the socio-economic and the biophysical. **Methods/Approach:** The latter is presented by means of emergy analysis, which is a system-based approach that measures the aggregate work of biosphere needed for the provision of goods or services in the units of solar energy joules. The novelty aspect of this paper is the introduction of emergy indicators into the standard socioeconomic optimisation model of the chosen agricultural production system. The optimisation model based on linear mathematical programming is designed to empirically investigate different alternatives to the sector's reorganisation. **Results:** The results of the optimisation models suggest considerable restructuring of the sector and, consequently, large discrepancies in the sector's performance. **Conclusions:** The results suggest that further expansion of organic production systems as a result of a stronger environmental focus in farm management would improve the sector from both, the socio-economic and the emergy perspective. Moreover, even pursuing certain socio-economic targets may improve the sector's biophysical performance and lower pressure on the local environment.

Keywords: agriculture, dairy sector, system approach, mathematical programming, emergy analysis,
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Introduction

Agriculture is a production system where the economic principles of organisation act in mutual dependence with its ecological boundaries (Smith et al., 2000; OECD, 2000; van Zanten et al., 2014). The mutual connectedness of agriculture with its local and global environment and the risks related to high complexity of their interactions may be understood as a source of increasing challenges that the agriculture is facing today.

On the other hand, a complex and often conflicting array of challenges that agriculture is facing (eg. diminishing production resources, volatile market conditions, production- and market-associated risks, environmental depletion) calls for a restructuring of the sector in terms of competitiveness and productivity improvements, taking full account of the requirements of sustainable development (Godfray et al., 2010; OECD/FAO, 2012). Various objectives of the common agricultural policy and an increased demand for interdisciplinary research approaches had an important role in the development of bio-economic models. These are in general known as (mathematical) models that link different disciplines in order to answer multi-dimensional questions about the organisation of agricultural production systems (Flichman et al., 2012). Bio-economic models as analytical tools that support the decision-making process need to embrace comprehensive economic evaluation with the limitations and requirements of the natural environment (Daily et al., 2000). However the integration of biophysical and economic components in technical and conceptual sense still remains the most significant challenge in this field (Flichman et al.,2012; Gasparatos et al. 2009, Gasparatos et al.,2012).

Emergy analysis (Odum, 1983, 1988, 1996) is a system-based environmental accounting approach that measures the aggregate work of biosphere needed for provision of any good or service. Based on a biophysical understanding of value, the analysed processes are broken down into the stocks and flows of natural capital invested in the production and quantified in physical units, solar energy joules (seJ). As such to define and quantify the contribution of ecological processes in the production of any good or service. In contrast with the conventional economic evaluation, which is anthropocentric in its nature with commonly rather reductionist viewpoint, emergy analysis provides a system based eco-centric perspective on agricultural activity (Brown et al., 2004, 2010, Odum 1988, 1996). The emergy approach has been extensively used to investigate several different agricultural systems, either at a farm (La Rosa et al., 2008; Hu et al., 2012), provincial/regional (Li et al., 2012; Ghisellini et al., 2013) or national level (Rydberg et al., 2006; Chen et al., 2006). It has been successfully implemented to evaluate and compare biophysical functioning of alternative production systems, that differ either in the type of agricultural activity (Lefroy et al., 2003), in production technology (Castellini et al., 2006; La Rosa et al., 2008), or have different spatial or time-scale (Chen et al., 2006; Vigne et.al., 2013). A comparison of emergy and economic characteristics of systems investigated is less common (e.g. Lu et al., 2010; de Barros et al., 2009), but often recognised as a complementary approach that provides additional information needed for a more comprehensive perspective on agricultural performance (Jaklic et.al., 2014).

With the ambition to improve the quality of decision-making processes in agriculture by applying a more complete perspective, this paper attempts to incorporate emergy indicators into standard socioeconomic optimisation models. This is illustrated by investigating performance of a chosen agricultural production system from multiple perspectives and taking into account various sets of optimisation criteria. More specifically, the paper builds on the case of dairy production in Slovenia. Dairy production is chosen as it presents a case of a complex agricultural production system. In terms of the sector’s relevance for the country studied, dairy production is the predominant sector in Slovenian agriculture that contributes the most towards the national agricultural output. By the same token, dairy sector is also the largest single consumer of natural resources available in the country. In the last decade the sector has undergone massive (mainly economically driven) restructuring. The number of dairy farms has decreased substantially, those remaining in the sector mainly increased the herd size, specialised and modernised their production. Despite the overall productivity and quality improvement of the country's dairy sector, the aggregate quantity of production remained largely unchanged.

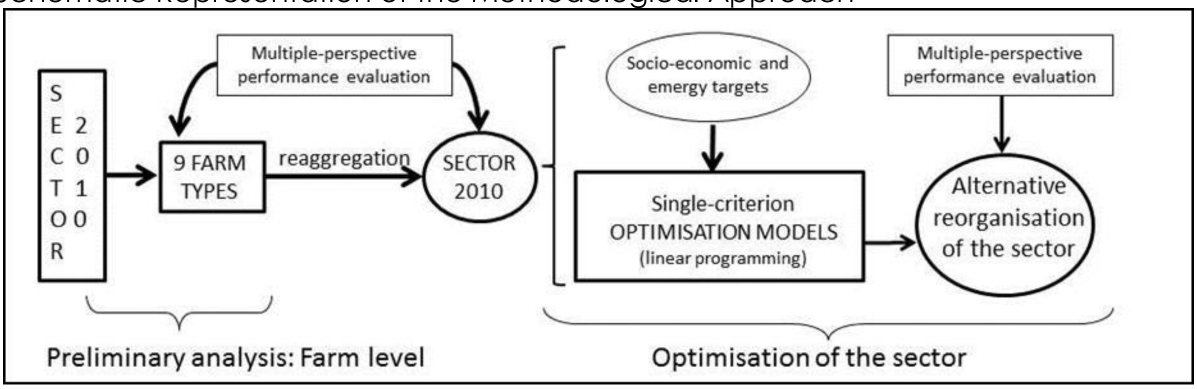
The paper is organised as follows. The section 'Material and methods' describes the steps and procedures applied in the empirical analysis of the structure and performance of dairy production in Slovenia. The sector is disaggregated into nine farm types, representing the variety of the production systems in the country. The section continues with theoretical specification of the optimisation model and outlines the optimisation criteria (socio-economic- and emergy-related). In order to link the main findings with their (policy, research) implications, the 'Results and discussion' are treated together in one section.

Material and methods

Methodological approach- schematic representation

The mathematical modular tool aimed to investigate Slovenian dairy sector was developed in two stages. The methodological approach is schematically represented in Figure 1. Firstly, in a preliminary analysis Slovenian dairy farms were broken down into nine 'typical' production types that were further evaluated from socio-economic and biophysical (emergy based) perspective. By farms' re-aggregation, the model of the dairy sector in 2010 was specified. With its characteristics (farm, production structure, economic and biophysical emergy performance) it served as a baseline reference to the model solutions obtained from the optimisation model developed.

Figure 1
Schematic Representation of the Methodological Approach



Source: Author's illustration

The development of the optimisation model at the national level represents the central focus of the research presented in the paper. The model is based on linear programming paradigm and served as a supportive tool to investigate various alternatives to sector's reorganisation pursuing a single optimisation criterion (e.g. income, production, system sustainability). It also served to determine the optimal (min/max) values/characteristics that the sector can potentially reach under each optimisation scenario. Finally, the model solutions were evaluated, compared and positioned according to their performance in socio-economic and emergy terms.

Preliminary analysis of model farm types

In a preliminary analysis the farms engaged in dairy production in Slovenia were categorised into nine production types. These represent the diversity of farm types engaged in dairy production in Slovenia. They range from subsistence producers (FT1), to semi-subsistence oriented farms (FT2), and a limited, but growing number of organic producers, varying in production intensity and in the degree of market presence (FT3 and FT4). The conventional production systems are prevailing, although they significantly differ in several parameters, such as herd size, choice of breeds, size and structure of utilised agricultural area, and the quantity and origin of compound feed (FT5 to FT9). Basic farm characteristics (Table 1) that derived from the Agricultural Census 2010 performed by Statistical office of Slovenia and from the Central Cattle Breeding database from Agricultural institute of Slovenia were used for describing production resources, technological and economic parameters of each farm type, and to quantify key human-controlled and environmental outputs and input flows to the dairy production systems.

Table 1
Basic Farm Type Characteristics (year 2010)

	FT1	FT2	FT3	FT4	FT5	FT6	FT7	FT8	FT9
farm type	subsistance	half-subsistance	extensive organic	intensive organic	conven-tional	smaller intensive	highly intensive	larger intensive	agricult. enterprise
Breed*	S, BS	S, BS	S, BS	S, BS	S, BS	HF, S, BS	HF	HF	HF
Dairy cows	2	8	4	26	20	46	51	105	654
Milk yield**	3,600	4,500	3,000	4,500	5,500	7,400	9,300	7,500	7,000
UAA***	4	9	9	44	17	37	37	90	762
crop area	11%	19%	8%	13%	37%	56%	59%	53%	58%
terrain	steep/ hilly	steep/ hilly/ flat	steep/ hilly	hilly/flat	hilly/flat	hilly/flat	flat	flat	flat

* S-Simmental, BS- Brown Swiss (BS) HF- Holstein–Friesian breed
** kg/cow per annum
*** utilised agricultural area (ha)

Several socioeconomic and emergy performance indicators were calculated. These provided an insight into the differences between the farm types' in their profitability, productivity and farmer's income independence and environmental impact of the production (socioeconomic indicators), as well as biophysical efficiency, system's sustainability and utilisation of local resources (emergy indicators). A more detailed insight to the methodology, selected indicators and the results of the preliminary analysis can be found in Jaklič et al (2014).

Definition of the optimisation modelling tool at the national level

In the subsequent step of the analysis, the status of the dairy sector in 2010 was reconstructed from the nine farm types identified in the preliminary analysis. The main specifications of the sector, such as the structure of the sector, total production, income, number of animals and intensity of production, as well as various socio-economic and biophysical performance characteristics were identified. The model of the sector in 2010 provided a reference and a baseline for the development of the optimisation model, formulated to look for an optimal (farm) structure of the sector that will satisfy the particular objective(s).

The optimisation modelling tool is supported by different single-criteria models based on linear mathematical programming (LP). LP is defined as a maximisation or minimisation of a single linear objective function (*r* for maximisation and *k* for minimization) with a feasible area of solutions that is determined by a set of linear constraints. This is mathematically represented as:

$$\max Z_r = \sum_{q=1}^{Q} c_{rq} x_q \qquad \textit{for all } r = 1 \textit{ to } n \tag{1.1}$$

s.t.

$$\sum_{q=1}^{Q} a_{iq} x_q \le b_i \qquad \textit{for all } i = 1 \textit{ to } m$$

$$x_q \ge 0$$

$$\min Z_k = \sum_{q=1}^{Q} c_{kq} x_q \qquad \textit{for all } k = 1 \textit{ to } t \tag{1.2}$$

s.t.

$$\sum_{q=1}^{Q} a_{iq} x_q \le b_i \qquad \textit{for all } i = 1 \textit{ to } m$$

$$x_q \ge 0$$

where Z is an objective function, r is an index that defines the objectives that are subject to maximisation (1.1) and k for the ones that are minimised (1.2), x_q are decision variables that in our study represent a number of farms within each farm type (Table 1), where q is an index that determines a farm type and Q is a total number of farm types, c_q are an objective function coefficients and a_{iq} technical coefficients of each farm type. A set of constraints that restricts the values that may be assumed by decision variables is represented by b_i .

The number of dairy farms within each farm type x_q denotes a key model variable and the original model solution. This solution that directly indicates a structure of the sector, indirectly determines values of other characteristics of the sector, such as an average farm size, number of animals, land structure, soil eroded, structure of natural resource use etc.

The model includes set of constraints (b_i) that present the sector's boundaries that are defined by agricultural land intended for dairy production in 2010 and remain fixed through the entire modelling process. Furthermore, the problem of transition between different farm types is considered by incorporating additional constraints. These describe the possibility of the reorganisation of one type of a farm into another, taking into consideration the comparability and differences in farming conditions between the types, such as larger discrepancies in their size, terrain on which farms are located and production technology.

The objectives (r,k) applied in the models relate to farm and sector level indicators of socio-economic and emergy based performance. Socioeconomic performance focuses on objectives related to income of a farmer and the sector, productivity and employment, public payments and global environmental impact. Emergy criteria on the other hand pursue biophysical efficiency and intensity of emergy use, pressure on local environment and sustainability of the production system. The objectives are listed and shortly described in Table 2.

Table 2
Socio-economic and emergy-related objectives simulated in single-criteria optimisation models

Socioeconomic indicators / objectives		**Max Z_r /min Z_k**
Income	Total income in the sector is the aggregated income of dairy farms	Max INC
	Hourly wage is income received per hour of labour (PP incl.)	Max HW
Productivity	Total production of the sector is derived by weighting and adding-up of the production of dairy farms	Max Q
	Intensity of production defined in terms of the annual yield of the milk per cow	Max INT
Employment	Number of employed persons (1 person equals 2000 working hours)	Max EMPL
Public payments	Total amount of public payments (PP)	Min PP
	Dependence of PP is defined as share of PP in farm's income	Min %PP
Environmental impact	Total GHG emissions of total sector's production	Min GHG
	Relative burden of GHG is defined as emissions released per unit of production	Min GHG/Q
Emergy indicators / objectives		
Biophysical efficiency and intensity of emergy use	Unit Emergy Value (UEV) indicates biophysical efficiency of a system in emergy use and renewability of a system	Min UEV
	Emergy Density (ED) is emergy per hectare and denotes emergy use intensity	Max ED
Exploring renewable local resources and system sustainability	Environmental Loading Ratio (ELR = total non-renewable emergy (NMLS)/local renewable emergy(R)) indicates pressure of the system on local environment. Higher fraction of renewable emergy in total emergy use (%R) will as a measure of long term sustainability improve the indicator.	Min NMLS = Min ELR (NMLS= local non-renewable emergy, purchased emergy and emergy of labour and services)

Evaluation and ranking of model solutions

In the final stage the solutions of the optimisation models were evaluated and compared according to the socioeconomic and emergy indicators of sector's performance listed and defined in Table 3.

The indicator values were normalised in a way to allow for their relative comparison to the reference performance in 2010, as shown in Formulae 2.

$$N_i = P_i/P_{i2010} \qquad i = 1, \dots p \qquad (2)$$

Where N_i is a normalised and P_i is an original value of the i^{th} indicator and P_{i2010} the value of this indicator in a reference year 2010. Based on the total deviation from the reference values, each solution was positioned and ranked according to their overall socio-economic and emergy performance.

Table 3
Socioeconomic and Emergy Indicators of Sector's Performance

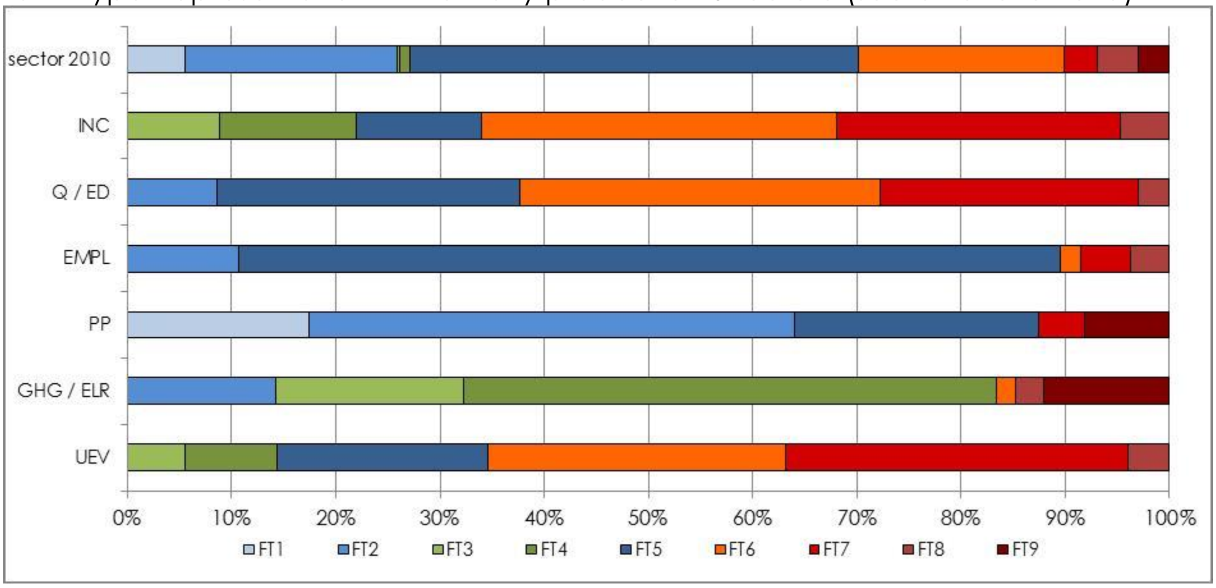
Socioeconomic indicators		Emergy indicators	
Income	Total income in the sector*	*Emergy use*	Unit Emergy Value (UEV)*
Production	Total production in the sector*		Emergy Density (ED)*
Employment	Number of employed persons*	*Interaction with local*	Emergy Yield Ratio (EYR) reflects the system's ability for exploitation of free local resources
Public payments (PP)	Total amount of PP*	*environment*	Environmental Loading Ratio (ELR)*
Income	Share of PP in total income*	*System*	The share of renewable emergy in the total emergy use (%R)
stability	Hourly wage*	*sustainability*	Emergy Sustainability Index (ESI) is a ratio between the sector's ability to exploit local resources and pressure of a system to local environment
	Income sufficiency is a share of work that is fully paid with income earned (PP excl.)		
Environmental impact	Greenhouse gas emissions (GHG)*	*Emergy exchange*	Emergy exchange ratio(EER) unveils the relative trade advantage in emergy exchange(producer vs. purchaser)
	GHG per unit of production*		

*More in detail described in Table 2

Results and Discussion

Figure 2 shows farm type representation in the total dairy production according to the results of single-criterion optimisation model solutions (optimisation criteria listed in Table 2). Due to higher relevance of the solutions that pursue sector-level targets the figure solely presents these. The results indicating structural differences of the sector when other farm-level optimisation objectives are pursued are discussed in the text and in quantified form fully presented in the Appendix A.

Figure 2
Farm Type Representation in the Dairy production Structure (sector level criteria)



INC: income; Q: production; ED: Emergy density; EMP: employment; PP: public payments; GHG: greenhouse gas emissions; ELR: Environmental loading ratio; UEV: Unit emergy value
Source: Author's illustration

The results show distinctive differences in the production structure when pursuing different objectives. In the reference year 2010 the production was distributed mainly to the production at smaller conventional farms (68.9%) and partly to larger intensive farms (29.9%), while the organic farms made an insignificant contribution to the total production(1,2%). From the production structure of the alternative formulations of the sector three clusters of model solutions, categorised according to the share of organic production may be identified. First cluster includes the model solutions with relatively low or zero organic production. For example, further intensification of the sector, which would lead to highest possible productivity as well as emergy use intensity (Q / ED) may completely supplant organic production. Similar may happen in case where the focus lies solely on achieving high employment, lowest budgetary burden of the sector or lowest dependence of income on public payments. Contrary, the second group of model solutions may be identified by sector's significant reliance on organic production. These are the solutions that present the sector with lowest pressure on the global and local environment (GHG and ELR respectively) as well as the solution that reflects the sector with highest hourly wage (HW). Finally, a relatively balanced production structure that encompasses a fair share of organic production as well as production based on conventional production technology at smaller, less intensive and larger, highly intensive farms can be recognised in model solutions that achieve highest income (INC) of the sector, highest biophysical efficiency (UEV) as well the solution that represent the production system with lowest GHG emission release per unit of production (GHG/q).

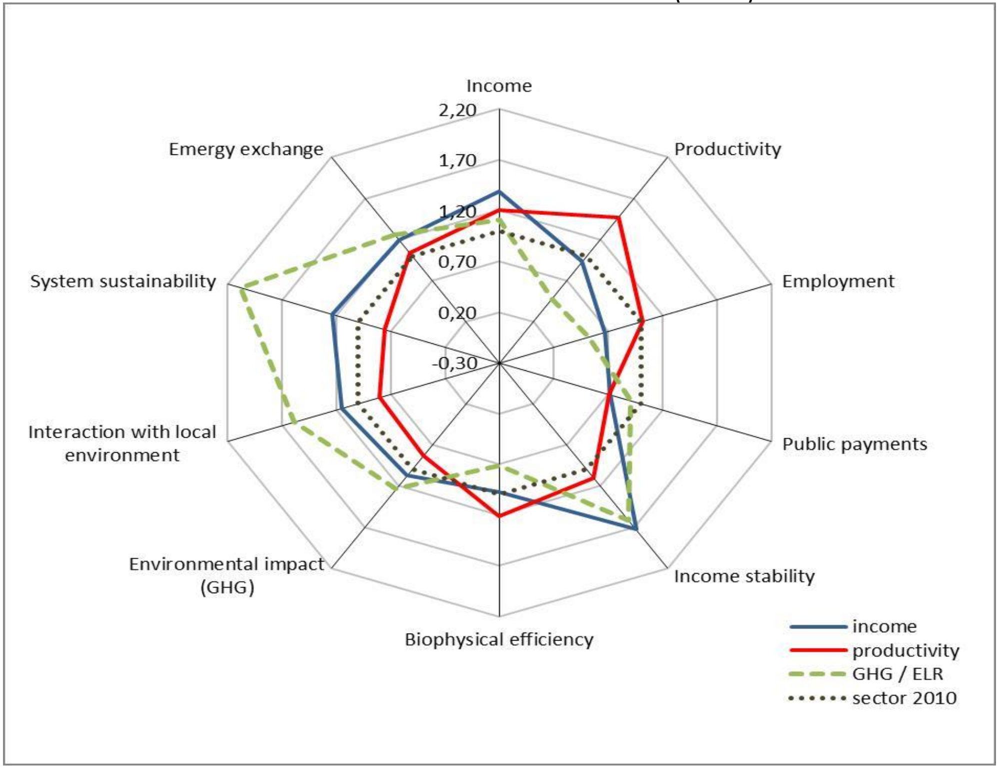
Figure 3 illustrates discrepancies in selected indicators measuring the performance of the dairy production system between the sector in 2010 and three scenarios of its reorganisation. The values presented are normalised and adjusted so that higher value indicates better performance.

Larger and even diametrical characteristics may be noted especially for the solutions pursuing highest productivity and the best environmental performance from the perspective of lowest emission release and lowest pressure on local environment. The results of the productivity-focused scenario show that the production structure that solely relies on conventional, mostly highly intensive production, markedly improves sector's productivity, biophysical efficiency, as well as income related criteria. However, such reorganisation of the sector that is based solely on conventional, mostly highly intensive production (Figure 2) is highly dependent on non-renewable resources (96.5 %), which harmfully affect the environment, both locally and globally, thus representing an evident step-back in terms of the system's sustainability.

Conversely, production planning that leads to restructuring of the sector that prioritises organic production, yields a sustainable production structure, characteristic for a relatively high share of renewable emergy used in the system (8.9%), while the sector's pressure on local environment is low and its ability to exploit free local resources is high. However, this solution also brings unfavourable results in terms of a considerable productivity decrease and the corresponding knock-on effects on employment. Low productivity is also the vital reason for low environmental impact that is in relative terms (per unit of production) higher than the reference (sector in 2010).

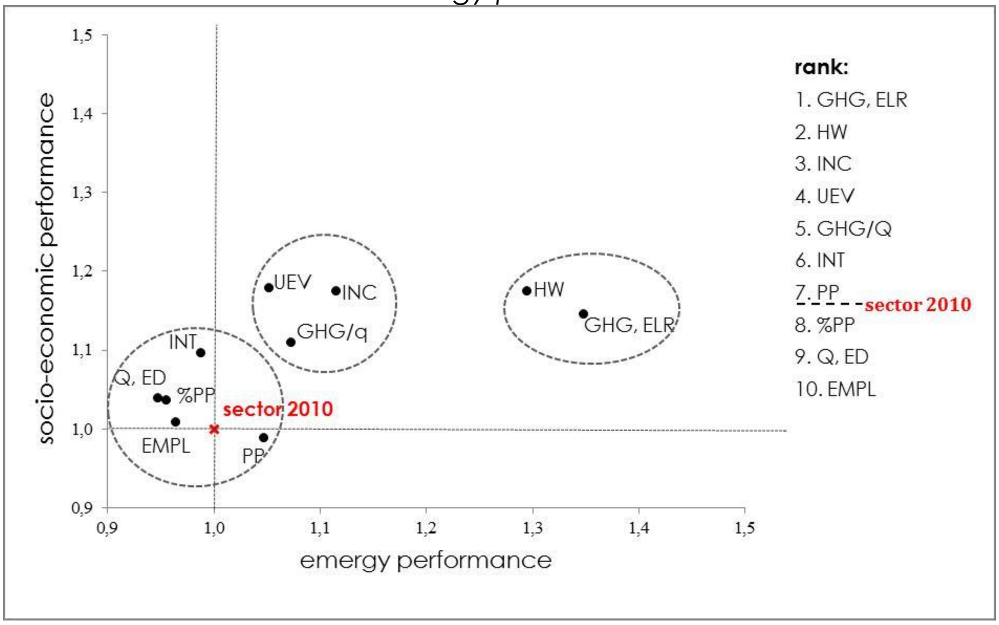
Finally, the solution that targets the sector with highest income seems to emphasise the advantages and to reduce the weaknesses of the other two. Comparing to the sector in 2010, it achieves considerably better results in most of the socio-economic and emergy based performance criteria, although at the expense of noticeably higher budgetary support and significantly lower employment in the sector.

Figure 3
Discrepancies in Selected indicators describing performance of the dairy sector between the model solutions and the baseline (2010) situation



Source: Author's illustration

Figure 4
Classification and multiple-perspective position of model solutions with respect to their socio-economic and emergy performance.



Source: Author's illustration

Furthermore, all of the model solutions were positioned and ranked according to their performance, illustrated by a set of socio-economic and emergy indicators.

Again, illustrated in Figure 4, three clusters of model solutions can be noted. The results show that half of the solutions define the production system that is performing better that the reference sector from both, socio-economic and biophysical perspective. The solutions that represent the sector with lowest pressure on global and local environment as well as the solution with highest hourly wage in the sector are ranked the highest. This is contributed to their significant emergy performance that results from sector's strong orientation to organic production.

Similarly, reorganisations of the sector that achieves highest income, highest biophysical efficiency or lowest emission release per unit of production further highlights the possibilities to sector's overall improvement though pursuing a well balances production structure of the sector.

On the other hand, the rest of the model solutions represent production systems that perform better than the reference either from socio-economic or biophysical perspective. The solution representing the sector with highest intensity of production and the solution with lowest budgetary burden are performing slightly better than sector in 2010 when the whole set of ranking criteria is considered. However, the first one is ranked higher due to a notably better socio-economic position and the second due to its better biophysical functioning. Lowest ranking forms of sector's reorganisation are presented in model solutions pursuing lowest share of public payments in total income, highest productivity or emergy use intensity and finally highest employment in the sector. Although these solutions represent the sector with slightly better socio-economic characteristics than the sector in 2010, this does not weights out their poor biophysical functioning and ranks them even below the sector in 2010.

Conclusion

The main innovation aspect of this paper is incorporation of emergy analysis into the conventional production planning models in agriculture. By incorporating both, an economic (anthropocentric) and emergy based (eco-centric) indicators, the multiple-perspective model aims to provide more comprehensive evaluation of the sector's performance and of various alternatives to its reorganisation.

The results presented in the paper underline that joint application of emergy and economic criteria to the sector's optimisation brings mutually reinforcing results. The results underline the link between the intensification of production and the sector's overall improvement. Moreover, solutions suggesting a wide and diverse range of agricultural holdings with a balanced production structure are leading us to the conclusion that improvement of both, socio-economic and biophysical performance of the sector can be achieved even by pursuing only socio-economic objectives. However, the results clearly propose that representation of organic production plays a substantial role in such improvements.

The proposed approach has a major drawback in terms of the applicability of the results. Namely, the model is simplified in a manner that does not allow for reallocation of resources between various agricultural sectors. To our judgement, the shortcomings of this simplification can be circumvented by extending the modelling tool to other sectors competing for the same resources. However, this would demand substantial additional resources. Moreover, the results of single-criteria model solutions clearly show larger discrepancies in model solutions when different objectives are pursued. Since agricultural planning at the sector level is multiple-criterial in its nature, we see a great potential for the model improvement in developing a multiple-criteria optimisation modelling approach. Multiple-criteria analysis supported by goal programming or similar methodology could provide a better insight into the complexity of agricultural planning and therefore into possibilities of finding a compromise between conflicting objectives in decision-making processes.

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Appendix A *Farm structure and performance characteristics of single-criterion model solutions*

Optimisation criteria*		INC	HW	Q; ED	INT	EMPL	PP	%PP	GHG; ELR	GHG/Q	UEV
Farm structure	unit										
number of farms in the sector	num.	6.264	6.085	5.772	5.340	7.277	16.759	6.826	6.716	6.057	5.796
share FT1	%	0	0	0	0	0	62,62	0	0	24,81	0
share FT2	%	0	0	35,58	0	28,22	31,72	30,08	16,37	0	0
share FT3	%	65,81	67,75	0	35,09	0	0	0	65,14	20,87	52,13
share FT4	%	9,82	20,64	0	4,05	0	0	0	17,98	15,98	8,59
share FT5	%	9,75	10,04	40,33	34,81	69,77	5,37	63,07	0	30,69	21,08
share FT6	%	8,95	0	15,54	16,8	0,55	0	0	0,24	0	9,68
share FT7	%	5,12	0,36	7,97	8,61	0,99	0,24	6,74	0	7,59	7,93
share FT8	%	0,54	1,21	0,59	0,63	0,47	0	0,06	0,15	0	0,58
share FT9	%	0	0	0	0	0	0,04	0,05	0,11	0,07	0
Performance indicators											
Socio-economic performance indicators											
Income	000 €	127.490	107.575	110.551	119.994	93.610	79.679	98.177	101.195	106.638	125.193
Production	t	561.78	335.54	886.33	806.34	713.68	425.86	791.87	285.44	584.373	668.50
Employment	pers.	5.622	4.593	8.559	7.296	9.572	8.197	9.227	4.383	6.279	6.325
Public payments (PP)	000 €	66.069	59.368	66.887	70.023	52.629	39.873	54.712	56.594	58.869	66.743
Share of PP in total revenues	%	18,00	21,10	14,30	15,50	13,90	14,7	13,3	21,80	16,5	16,60
Income sufficiency		0,64	0,62	0,30	0,40	0,25	0,29	0,28	0,60	0,45	0,54
Greenhouse gas emissions (GHG)	t eq CO_2	655.616	407.644	1.019.543	921.474	835.707	549.597	896.196	360.843	651.302	762.873
GHG per unit of production	t eq CO_2/t	1,17	1,21	1,15	1,14	1,17	1,29	1,13	1,26	1,11	1,14
Emergy indicators											
Unit emergy value		1,54	1,77	1,56	1,53	1,68	2,02	1,62	1,89	1,6	1,53
Emergy density		208,1	142,01	331,49	295,35	288,09	205,98	306,96	129,04	223,98	244,51
Emergy yield ratio		1,09	1,13	1,06	1,07	1,07	1,09	1,07	1,15	1,09	1,08
Environmental loading ratio		17,12	11,36	27,86	24,72	24,08	16,93	25,73	10,23	18,5	20,29
Emergy sustainability index		0,06	0,1	0,04	0,04	0,04	0,06	0,04	0,11	0,06	0,05
Fraction of renewable emergy		0,06	0,08	0,03	0,04	0,04	0,06	0,04	0,09	0,05	0,05
Emergy exchange ratio		1,11	1,03	1,33	1,25	1,42	1,43	1,39	1,02	1,21	1,17

* INC: income; HW: hourly wage; Q: production; INT: intensity of production; EMP: employment; PP: public payments; %PP: share of PP in total revenues; GHG: greenhouse gas emissions, GHG/Q: GHG per unit of production; ED: Emergy density; UEV: Unit emergy value, ELR: Environmental loading ratio